COSMIC RAYS AT EXTREME ENERGIES

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Interest in extremely high energy cosmic rays has increased rapidly in the last decade. More important perhaps is that that interest now extends well beyond the "usual suspects" to include members of the wider astrophysics and high energy physics communities. Factors which have contributed to this development include: a keener appreciation of the difficulties associated with cosmic ray production at these energies; increased confidence in the energy and mass estimates made by the "unconventional" detectors used in ground based cosmic ray research; a realization that cosmic rays at these energies may serve as a unique probe of the extreme astrophysical environments where they are produced, and of the environment between the source or sources and our own galaxy; and lastly, the widespread availability of technologies such as digital wireless telecommunications and GPS-based time synchronization systems which make construction of new more powerful detectors feasible.

1 Extremely High Energy Cosmic Rays: An Introduction

Cosmic rays were discovered by the Austrian physicist Victor Hess in 1912. Efforts to determine their nature — their composition, source, and spectrum — soon followed. Eighty years have elapsed and these goals have not changed. Now however, detectors cover thousands of square kilometers; the energies of interest exceed $10^{18}eV$ ($\equiv 1\,EeV$); and the most likely sources, however unlikely they may be, lie far beyond the confines of our galaxy.

In the 1930's Pierre Auger introduced a new era in the study of cosmic rays when he observed "extensive air showers" (EAS) — particle cascades initiated in the upper atmosphere by the interaction of energetic cosmic rays. Auger deduced that the cosmic ray spectrum extended up to and perhaps beyond $10^{15}eV$. Beginning in the 1960's, air shower detectors were constructed with relatively large areas (i.e., a few square kilometers). These efforts were motivated in part by the realization that cosmic rays at a few EeV were unlikely to be confined by the Galaxy's magnetic fields. Thus, if sources at these energies were Galactic, the observed flux should exhibit a degree of anisotropy. No clear evidence for anisotropy was found. However, these detectors did observe extraordinarily energetic events — in excess of $10^{20}eV$!

Unfortunately, even now, little is known with certainty regarding the nature of these extremely high energy (EHE) cosmic rays [a]. The reason — *inadequate data, both in terms of the numbers of events observed and in the detailed characterization of those events.* Cosmic rays at these energies are rare; the flux above $100EeV$ is less than one per square kilometer per century! Moreover, it is air showers which are observed, never the primary cosmic rays themselves; thus, their nature may only be inferred.

[a] For a detailed discussion of the topics covered in this paper please see the Auger Project Design Report at www-td-auger.fnal.gov:82

2 The Observation of EHE Cosmic Rays

On reaching the ground a $10EeV$ proton (initiated) shower may contain 10^9 particles and cover an area of $20\,km^2$. Densities near the shower core — the location of peak particle density — can exceed 10^6 particles m^{-2}. While density falls rapidly away from the core, at one kilometer the number of $e^{\pm}$ and muons is still a few per square meter and of gamma-rays perhaps $100\,m^{-2}$. Though large at the surface, a shower's maximum size generally occurs above ground level where they may contain 10^{11} particles. Passage of this enormous cascade through the atmosphere produces fluorescence emission (the latter via excitation of nitrogen).

Two distinctly different though complementary techniques can be used to observe EHE air showers. Surface arrays (e.g., AGASA, Haverah Park), which sample the lateral density distribution on the ground, and fluorescence detectors (i.e., Fly's Eye) which observe the longitudinal development of showers in the atmosphere.

2.1 Surface Arrays: Thin Sampling, Single Layer Calorimeters

Surface arrays consist of a number of widely spaced particle detectors designed to measure properties of the shower front such as its time-of-arrival, rise-time, and density (perhaps with some discrimination between electro-magnetic and muonic components). From these data core location and arrival direction are determined. The density is fit to a "lateral distribution function":

$$\rho(r) = k\, r^{\eta + r/4000}\, (r/800)^{1.03}, \tag{1}$$

from which in principal the total shower size and hence primary energy can be found ($\eta \sim 2.5$ and is a function of the shower's zenith angle and the primary energy). The form of the lateral distribution function depends on the nature of the detectors used. The expression above is for Haverah Park's water Čerenkov detectors (WCD) and is somewhat flatter than would be appropriate for an array of scintillation detectors; a result of the higher relative sensitivity of WCD to muons which are more broadly distributed in showers.

In practice, as Hillas [1] has shown, the density at some distance from the core provides a more robust measure of the energy — being less sensitive to fluctuations in shower development and to the initiating primary's mass. Thus, at AGASA for example, the energy is expressed as: $E(eV) = 2x10^{17}\rho_0(600)$ where $\rho_0(600)$ is the density $600m$ from the core of a vertical shower. Though surface arrays sample only a tiny fraction of the shower front their ability to reconstruct shower parameters is reasonably good. Typical energy and angular resolutions at $10^{19}eV$ are $\pm 30\%$ and 1.5° respectively, improving at higher energies. Mass resolution (or primary identification) is somewhat more problematic.

Two shower parameters useful as clues to the nature of the primary are the relative number of muons in the shower, and the shower front's "rise-time". The number of muons in a proton shower increases as $E^{0.85}$. If an iron shower is viewed as a superposition of 56 proton showers, each with 1/56th the total energy, the number of muons is $\propto A(E/A)^{0.85}$ with A equal to 56. Thus, an iron shower contains 80% more muons than a proton shower of the same energy. As for rise-time, showers initiated higher up or which develop more rapidly produce shorter rise-times. Such is the case for heavier nuclei — in part simply due to their higher geometrical cross-section. Rise-time is in fact an indirect measure of X_{max} — the depth in the atmosphere at which the shower reaches maximum size. X_{max} is perhaps the single most sensitive indicator of the nature of the primary; it is a parameter which atmospheric fluorescence detectors observe directly.

2.2 *Atmospheric Fluorescence Technique: Remote Calorimetry*

Unlike surface arrays, atmospheric fluorescence detectors observe the development of showers in depth rather than at a single depth. A fluorescence detector such as the Fly's Eye consists of a number of meter-sized mirrors, each with a cluster of photo-multiplier tubes, each of which views a particular segment of the sky. Showers above the detector are traced in the fluorescent emission they produce in the atmosphere.

In the simplest "monocular" implementation of the fluorescence technique one component of the shower's arrival direction is derived from the observed pattern of tube hits. The second component and the distance to the shower axis are found by minimizing an expression relating them to the time at which the shower is observed in each tube. Given the position and orientation of the shower and the light observed in each tube, the shower size and depth of maximum are found by fitting an expression for the shower profile. From Gaissier and Hillas [2]:

$$N_e(X) \propto N_{max} \left(\frac{X - X_0}{X_{max} - X_0} \right)^{(X_{max}-X_0)/70} e^{(X_{max}-X_0)/70}. \tag{2}$$

The shower energy is then a "calorimetric" measure of integrated track length: $E \propto \int N_e(X)dX$. The mono technique has been shown to be accurate using a sample of data in which showers were observed by two widely separated detectors (i.e., "stereo" events) where the event geometry, hence energy, is well determined. The energy resolution is $\sim 27\%$ for $E \geq 2x10^{18} eV$.

The expression above also yields the depth of both the first interaction X_0 and X_{max}. The latter is related to the mass of the initiating primary as in:

$$< X^A_{max} > = < X^p_{max} > \; - \; 55 \; Log_{10} \; A. \tag{3}$$

For iron and proton showers the mean depth of maximum is 700 and 790 $g - cm^{-2}$ respectively. Given that for monocular events the resolution in X_{max} is $\pm 60 \, g - cm^{-2}$, discrimination on an event-by-event basis is not possible.

While atmospheric fluorescence detectors offer benefits for the observation of EHE cosmic rays, they operate only on dark, clear nights. Thus their duty cycle is limited to $\sim 10\%$, significantly reducing their exposure. Moreover, they are sensitive to variations in atmospheric clarity which must be carefully monitored and modeled.

3 EHE Cosmic Ray Propagation

In searching for the sources of EHE cosmic rays, characteristics of their propagation are likely to play an important role.

3.1 *The Greisen-Zatsepin-Kuz'min Cut-off*

Greisen [3] and Zatsepin and Kuz'min [4] (GZK) showed that cosmic rays with energies above $\sim 5x10^{19} eV$ gradually lose energy (via the Δ^+ resonance) as they propagate through the cosmic microwave background. At 100 EeV protons lose a significant fraction of their energy in distances as small (on a cosmological scale) as $100 Mpc$. Similarly, EHE nuclei photo-disintegrate via the giant dipole resonance losing $3 - 4 \; nucleons/Mpc$ for energies above $2x10^{19} eV$; their range is strictly limited and for heavy nuclei is unlikely to exceed $20 Mpc$.

The GZK cut-off will play an important role in interpreting the observed EHE cosmic ray spectrum. If the spectrum extends much beyond $100 EeV$, the source must lie relatively near by ($\leq 100 Mpc$). Conversely, if the spectrum drops steeply beyond the resonance threshold, the source may be cosmological (assuming that such a drop is not intrinsic to the source).

3.2 Magnetic Fields and Particle Astronomy

Faraday rotation measures place an upper limit on the "pervasive" (i.e., uniform) intergalactic magnetic field (IGMF) at $1nG$ — though the actual value is generally held to be much lower. Beyond that, remarkably little is known of the magnitude and structure of the IGMF. Nevertheless, it is often assumed that the fields are randomly oriented and that plausible values for the field strength and coherence length (λ) are $1nG$ and $1Mpc$. For a $100EeV$ proton primary from a source at a distance of $50Mpc$, the angular deflection θ is $\sim 2^{\circ}$. To this must be added deflections due to the galactic magnetic field. For trajectories in the plane these can be significant ($\delta\theta \sim 6^{\circ}$); for most arrival directions they are typically 0.3°.

Given that angular deflections are generally small, particularly at the highest energies, the arrival direction of EHE cosmic rays should "point back" toward their sources. Hence, it may be possible to identify individual sources.

4 The Sources of EHE Cosmic Rays

Source scenarios for EHE cosmic rays can be divided into those which are exotic, the decay of super-symmetric "X" particles for example, and those which are extraordinary. The latter invoke conventional Fermi acceleration within environments as diverse as the jets of powerful radio galaxies and in accretion flows in clusters of galaxies.

4.1 The Exotic: Gamma-ray Bursts, Topological Defects

Exotic scenarios for the production of EHE cosmic rays run the gamut from the aforementioned "X" particles, to acceleration in ultra-relativistic winds associated with gamma-ray bursts (GRB), to their identification as Dirac monopoles.

Gamma-ray Bursts. The origin of gamma-ray bursts is as enigmatic as that of EHE cosmic rays. Naturally, the suggestion has been made that the two may in some way be related, often in conjunction with statements concerning their relative energetics. Models[6] for "cosmological" GRBs have been developed in which Fermi acceleration in ultra-relativistic shocks associated with the burst event would produce protons with energies to $10^{21}eV$.

If cosmological GRBs are the source of EHE cosmic rays, the observed flux at lower energies ($< 5x10^{19}eV$) must be isotropic and must exhibit evidence of a GZK cut-off; the flux at higher energies should be concentrated in the Supergalactic Plane [b], assuming GRBs are associated with luminous material.

Topological Defects (TD). In these models super-massive $10^{24}eV$ "X" particles produced in the collapse/annihilation of TDs decay to produce leptons and quarks; the latter in turn produce jets of mesons and baryons. Spectra in TD models tend to be much "harder" than those produced in Fermi acceleration; thus, dominating the flux above $10^{20}eV$ while making a negligible contribution to the cosmic ray flux below $10^{19}eV$. A result suggested by the "gap" in the observed flux between $10^{19.6}eV$ and $10^{20}eV$ hinted at in existing data.

4.2 The Extraordinary: Shock Acceleration

While scales in shock scenarios differ dramatically (in both time and space) the constraints are similar: particles must be confined during the period of acceleration and the rate of energy gain must exceed that of energy loss. The maximum energy can be related to the strength of the magnetic field and the size of the accelerating region as in:

$$E_{max\,EeV} \sim \ \beta\, Ze\, B_{nG}\, R_{Mpc} \equiv \ \beta\, Ze\, B_{\mu G}\, R_{Kpc} \tag{4}$$

where β is typically $\sim$ 0.01. At $10^{20}eV$ this constraint eliminates many candidate sources.

[b] Defined by the locally ($< 200Mpc$) non-uniform distribution of bright radio and optical sources.

Supernova remnants and the galactic disk and halo are excluded; similarly, active galactic nuclei (AGN), galactic clusters, and radio galaxy lobes, are unlikely to be sources of EHE protons except under the most optimistic conditions. Furthermore, careful analysis suggests that none of these candidates satisfy the additional requirement that energy gains exceed losses in the source environment. EHE protons lose energy via synchrotron processes and in photo-production interactions such as $p\gamma \to \pi^+ n$; the latter are more generally important. Photo-reactions limit (or reduce) cosmic ray energies in photon "rich" environments or when acceleration takes place over very long time scales as in galactic clusters.

At present the least unlikely candidate source of EHE cosmic rays seems to be in "hot-spots" associated with a sub-class of galaxies which are observed as bright, highly asymmetric radio sources. These hot-spots may mark the termination of powerful jets in the inter-galactic medium within which mildly relativistic shocks are expected to develop. The field strength within hot-spots and their size, based on observations of synchrotron emission, are $4x10^{-4}\,G$ and $20\,kpc$. Thus, Equation 4 suggests that proton primaries might reach an energy of $10^{21}eV$; in fact, some detailed models [5] of hot-spots require that such high energy primaries be present.

If the sources are conventional (sites of Fermi acceleration) then, as with cosmological GRBs, the flux at lower energies should be isotropic and exhibit a GZK cut-off and that at higher energies predominantly from the Supergalactic Plane. In all likelihood these sources should be clearly identifiable.

5 Status of EHE Observations

Above a few GeV the flux of cosmic ray is roughly proportional to E^{-3}. Though nearly featureless, the spectrum steepens slightly at $5x10^{15}eV$, recovering somewhat at $3x10^{17}eV$ (where γ the power-law index is $\sim -3.27 \pm 0.02$). In Fly's Eye stereo mode data the spectrum flattens still further near $4x10^{18}eV(\gamma \sim -2.71)$. The spectra reported by AGASA, Haverah Park, and Yakutsk (all surface arrays) exhibit similar though less distinct "dip-rise" features. In an *ad hoc* manner these latter flux measurements have been shifted in energy to agree with that of the Fly's Eye at $10^{18}eV$ (shifts of less than 10% are required, all to lower energies). The results are in very good agreement between $10^{18}eV$ and $10^{19.2}eV$.

Two features are worth noting at the highest energies. First, an apparent steep drop in flux at $10^{19.6}eV$. The second is that events are observed with energies well above GZK cut-off. Both the AGASA and Fly's Eye collaborations have published detailed and persuasive analysis of events with energies of $200EeV$ and $320EeV$ respectively. These results confirm earlier reports — as early as 1962 by Volcano Ranch, and more recently from Haverah Park — of such extraordinarily energetic events.

As suggested earlier, because EHE cosmic rays are only weakly deflected by the IGMF their arrival directions should cluster about that of their sources. For example, in the direction of near by strong radio galaxies. For the highest energy Fly's Eye event, such may be the case. The galaxy 3C134 lies within the "error box" associated with this event's arrival direction. However, the distance to 3C134 is unknown and if found to exceed $25-30Mpc$ it would be an unlikely candidate (the attenuation length of a $320EeV$ cosmic ray in the microwave background is $\sim 8Mpc$). Aside from this example, correlations with obvious candidate sources among most EHE events observed by AGASA and Fly's Eye are not generally evident.

Nevertheless, intriguing "correlations" do exist. The arrival direction of events above $4x10^{19}eV$ observed by Haverah Park are found at the $2.5-3\sigma$ level preferentially along the Supergalactic Plane; neither Fly's Eye nor AGASA data exhibit evidence for such a large scale anisotropy. Within errors, the arrival direction of the two highest energy events reported to date, Fly's Eye at $320EeV$ and Yakustsk near $200EeV$, are the same; one of Haverah Park's more energetic events ($69 EeV$) lies within 3° of AGASA's most energetic event. Lastly, among 36 events observed by AGASA above $4x10^{19}eV$, three pairs of overlapping events ($< 2.5^\circ$) are seen. The chance probability for such an occurrence is $\sim 2.9\%$.

6 Conclusion

The data obtained to date represent more than thirty years of effort and, if nothing else, would stand as a monument to persistance. They are often confusing, sometimes conflicting, and always fascinating. They establish beyond any reasonable doubt the existence of cosmic rays with energies far higher than any mankind will ever attain. They hint at the existence of discrete astrophysical sources of enormous power, of the universality of the cosmic microwave background, and just perhaps, of physics beyond the standard model. They are inadequate. They provide more than sufficient motivation to do better.

With more and better data, far more than currently available, there is hope, and with some justification, that discrete sources will be identified and that their spectra will be measured. Not only will particle astronomy then be a reality — and new vistas opened — but the efforts to characterize the sources of EHE cosmic rays will advance immeasurably.

The HiRes atmospheric fluorescence detector will, for a time, provide that data — though accumulating only half a dozen events per year above $10^{20}eV$. Later, if approved, the Auger Observatory will come "on-line". Auger is to be a hybrid detector combining the advantages of the fluorescence and air shower techniques. For every event — a 100% duty cycle — the surface array will provide core location, arrival direction, muon/electro-magnetic ratio, and more. For events in which both the surface and fluorescence detectors participate, analysis of the fluorescence data will be constrained by results from the surface array (and vice versa). While quite unlike HiRes' stereo fluorescence technique, Auger's hybrid operations provides similar benefits. Though, with an effective aperture of $14000\, km^2 - sr$, Auger will observe 70 or more events per year above $10^{20}eV$ (1 in 10 as hybrid events).

While exploring the nature of EHE cosmic rays let us not lose sight of the fact that a bit like the "dancing bear", the remarkable thing is that they exist at all!

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